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# Experimental investigation of subcooled flow boiling of R245fa in a narrow horizontal annular duct

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***Abstract* -** Subcooled flow boiling in a horizontal annular test section was investigated in a temperature-controlled experimental setup. The annular test section is installed as a part of the laboratory THELMA (Thermal Hydraulics experimental Laboratory for Multiphase Applications) built at Reactor Engineering Division of Jožef Stefan Institute. The unique characteristics of the temperature-controlled heating of the inner tube, in principle allow for a wide range of measurements, from subcooled boiling to the critical heat flux and above into the unstable film boiling regime. Transparent outer tube and a high-speed camera allow for visual investigation of two-phase boiling structures. In this study, first measurements of heat fluxes and visualization of flow boiling of refrigerant R245fa in horizontal annular configuration are presented and discussed.

***Keywords*:** Subcooled flow boiling, horizontal annular duct, R245fa, visualization.

## 1. Introduction

In many applications removal of high surface heat fluxes is required. Whether it comes from cooling of ever-decreasing size of electronic components [1] [2], large nuclear reactor cores [3] or efficiency of HVAC systems [4], boiling is often used as the main heat transfer mechanism as it enables higher heat flux densities than single-phase heat transfer. However, as boiling heat transfer greatly depends on the bubble dynamics, different boiling regimes are possible with heat transfer coefficient varying vastly [5]. For prediction of boiling heat transfer, many different concepts have been proposed and a large number of models suggested [6]. Ranging from a wide variety of boiling liquids, pressures, surface types and other influencing parameters, each model only covers some specific conditions [7]. No one has however, managed to propose a generalized model so far, which could be accurately and reliably used in any application. For further development, experimental investigation of the underlying boiling phenomena is of great importance. Many experiments in flow boiling were performed in various geometries and with various fluids [8]. Experimental data at higher heat fluxes, close to critical heat flux and beyond however, are scarce. To the knowledge of the authors, all experiments found in the open literature employ power-controlled boiling and critical heat flux (CHF) based on electrical resistance heating of inner rod or outer walls.

For investigation of flow boiling at high heat flux densities, close to the critical heat flux, a unique temperature controlled annular test section was recently constructed [9] [10]. The proposed test section is fundamentally different. Instead of electric resistance heating, the inner rod is designed as a heat-exchanging pipe. With special insert, it is heated from the inside by a secondary water circuit which enables temperature-controlled boiling of the primary fluid on the pipe’s outer surface. Therefore, experiments close and above the critical heat flux, even far into the unstable film boiling are in principle possible. A transparent outer tube and a high-speed camera enable rather detailed visualization of the two-phase flow patterns.

## 2. Experimental setup

From the geometrical point of view, our experimental setup is similar to the system used by Lie [11] and Chen et. al. [12], where the flow boiling was investigated in a 2 mm horizontal annular gap, but with refrigerant R134a and at lower mass flow rates. In our experiments, a Refrigerant R245fa was used as it boils at lower pressures. The design was thoroughly described in our previous work [9] [13]. The core of the experimental system is a horizontal annular test section. Boiling occurs on the surface of the inner copper tube with a diameter of 12 mm and the total length of 585 mm. The annular gap between the copper tube and the outer glass tube is 2 mm wide. To achieve a temperature-controlled boundary condition, test section is designed as a concentric tube heat exchanger. Water flowing inside of a copper tube transfers the heat to the refrigerant R245fa flowing on the outer surface causing it to boil. Outer surface of the cooper tube is uniformly polished to provide relatively uniform distribution of nucleation sites. Boiling can be observed with a high-speed camera through a 4 mm borosilicate glass tube. Specially designed finned structure inside of the cooper tube (see Figure 1) provides strong heat transfer enhancement and allows local temperature measurement along the axis. Thermocouples for wall temperature measurements are installed on several fins just below the boiling surface, while the thermocouples in contact with the water inside the channel measure the local temperature of the water flow. Based on known axial temperature profiles and the mass flow rate of water, the heat flux from water to the refrigerant can be determined [14].Two thermocouples at the water and refrigerant inlets are used to measure the fluids inlet temperature, while the two two-junction thermopiles are used to determine the temperature difference between the inlet and outlet. From this, a total calorimetric power on the test section can be calculated. All thermocouples on the test section are referenced to the Kaye-170e triple point of water and NI-PXIe 500 with LabVIEW software is used for data acquisition. Two Micro Motion Emerson Coriolis flow meters are used for direct measurements of water and refrigerant mass flow rates, with the declared accuracy of 0.5% over the entire range of measured data.

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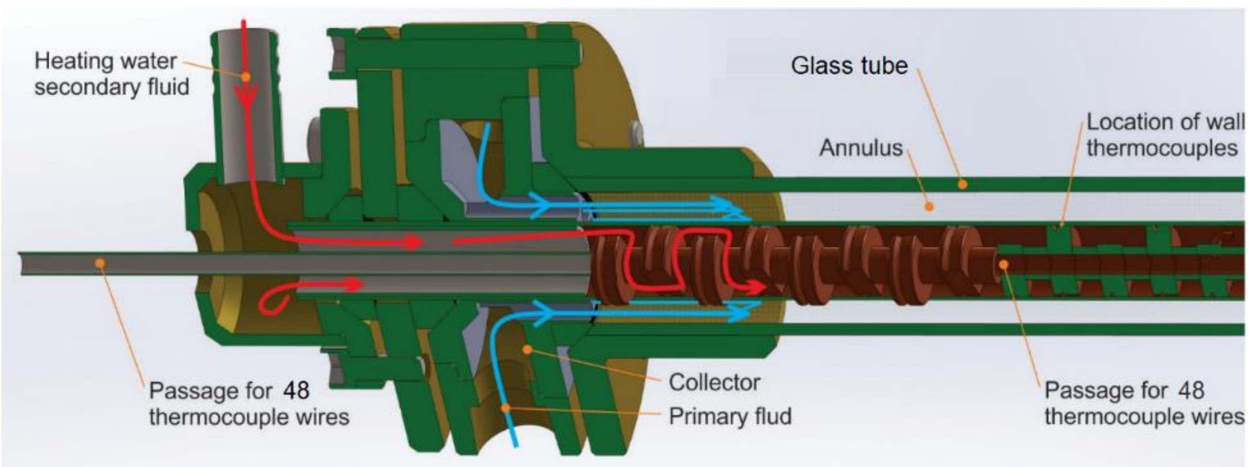


Fig. 1: Schematic view of the inlet region of the water-heated annular test section.

High-speed imaging is performed with a black and white Phantom camera v1212 from Litron with the maximum resolution of 1280 × 800 pixels and maximum of 20,000 frames/s. Tokina 100 mm Macro F2.8 optical lens is used for boiling observation. For improvement of brightness and contrast, a wide-angle LED lighting panel is used for illumination from the back. As no specific focal point is required in this application, recordings were performed with high aperture to increase the depth of the field. The test section itself allows the water flow reversal to enable the operation in co-current or counter-current flow regime. The counter-current flow regime provides a steady rise of refrigerant temperature towards the outlet and an increasing superheat, enabling the investigation of different boiling regimes along the test section. The co-current regime has the advantage that boiling only appears near the inlet, and fades away towards the outlet, as both fluid temperatures tend to equalize. The test section can be tilted from 0° (horizontal) to 90° (vertical) in order to study gravity effects on flow boiling at different inclination angles.

## 3. Results and discussion

For initial testing and validation of the system, measurements of subcooled flow boiling were performed in horizontal orientation of the test section. Several measurements in both co-current and counter-current flow configurations were conducted. After confirming that the system reached steady-state in each configuration, several recordings of about one second were performed with the frame rates of 5 kHz and exposition of 10 µs. Where possible, stream-wise temperature profiles were also measured. In each case, the data were collected in a time span of 20 min, every 10 seconds and were then averaged.

In counter-current regime, only visual investigation of boiling was possible due to malfunction of thermocouples near near the outlet region. Only the region close to the outlet was observed, as this is the region where the boiling is most intense. intense. The results at four different mass flow rates are presented in Figure 2. The refrigerant R245fa starts boiling at the the local saturation temperature of 30°C, with inlet subcooling of 3°C (inlet temp. 27°C) and inlet pressure 1.79 bar. The inlet temperature of the heating water is 60°C.

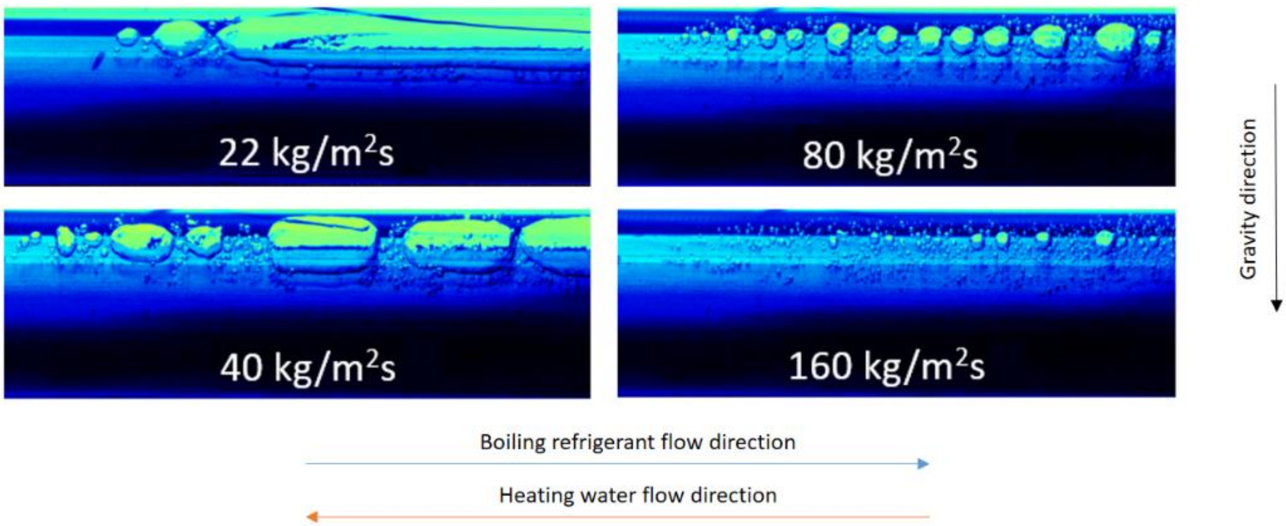


Fig. 2: Recordings of flow boiling in counter-current flow regime. R245fa flows from left to right, heating water from right to left. The colour scheme is only for contrast enhancement and corresponds for different luminosities.

At the lowest mass velocity of 22 kg/m$^2$s, the bubbles are moving very slowly and quickly merge to larger bubbles, eventually forming a single large continuous vapour patch stretching in stream-wise direction down to the outlet. From the first active nucleation site, the boiling continues with bubbles forming all along the edge of vapour patch. By increasing the mass velocity to 40 kg/m$^2$s, smaller bubbles continue to coalesce into larger vapour patches until they detach from the surface periodically and travel down-stream with the flow. Bubble coalescence becomes much weaker at mass velocity of 80 kg/m$^2$s, where no elongated vapour structures emerge, but mainly larger spherical bubbles are formed. At these conditions, many more smaller bubbles can be observed than at a lower mass velocities, which indicates that a higher mass velocity causes earlier bubble detachment from the nucleation site and therefore prevents further growing of the bubble due to evaporation on the heated surface. This is even more evident at the mass velocity of 160 kg/m$^2$s. Here the coalescence into larger bubbles also occurs very rarely. At the highest mass velocity (at 320 kg/m$^2$s, not shown in the figure) practically no coalescence can be observed.

The boiling flow patterns in co-current flow regime are shown in Figure 3. In this regime the heat transfer measurements and visual recordings can be done simultaneously. This time the flow boiling in the region close to the inlet was observed. Experiments were performed at two different saturation conditions, at ($T_{sat}$= 25°C, $p_{sat}$= 1.49 bar) and at ($T_{sat}$ = 30 °C, $p_{sat}$= 1.79 bar). Higher mass velocities were chosen for this configuration, ranging from 160 to 790 kg/m$^2$s. Due to the prevalence of drag forces over buoyancy, the top-bottom symmetry of the flow increases at higher flow rates. This is important for accurate determination of surface temperature and heat flux density, as the thermocouples are located in a single plane inside the copper tube and cannot properly measure the asymmetric distribution of vapour and liquid phase.

While no large differences are visible when comparing flow regimes at both saturation temperatures, it is clearly visible that the bubbles are smaller at $T_{sat}$ = 30°C, which is expected due to about 20% higher system pressure at this temperature. This difference in bubble sizes also explains why bubbles gathering at the top is more noticeable at lower saturation temperature, $T_{sat}$ = 25°C.  Due to high temperature differences at the inlet in co-current flow, periodical drying and re-flooding was still present at the lowest mass velocity of 160 kg/m$^2$s. Like in counter-current regime, plug flow instead steady boiling is expected at lower flow rates due to accumulation of vapour at the top. At 315 kg/m$^2$s, a complete dry-does not happen anymore, but the formation of bigger bubbles at the top is still visible. At 470 kg/m$^2$s and above, this phenomenon is less noticeable and a quantitative analysis of bubble parameters from the recordings will be required in to extract the basic bubble and flow parameters.

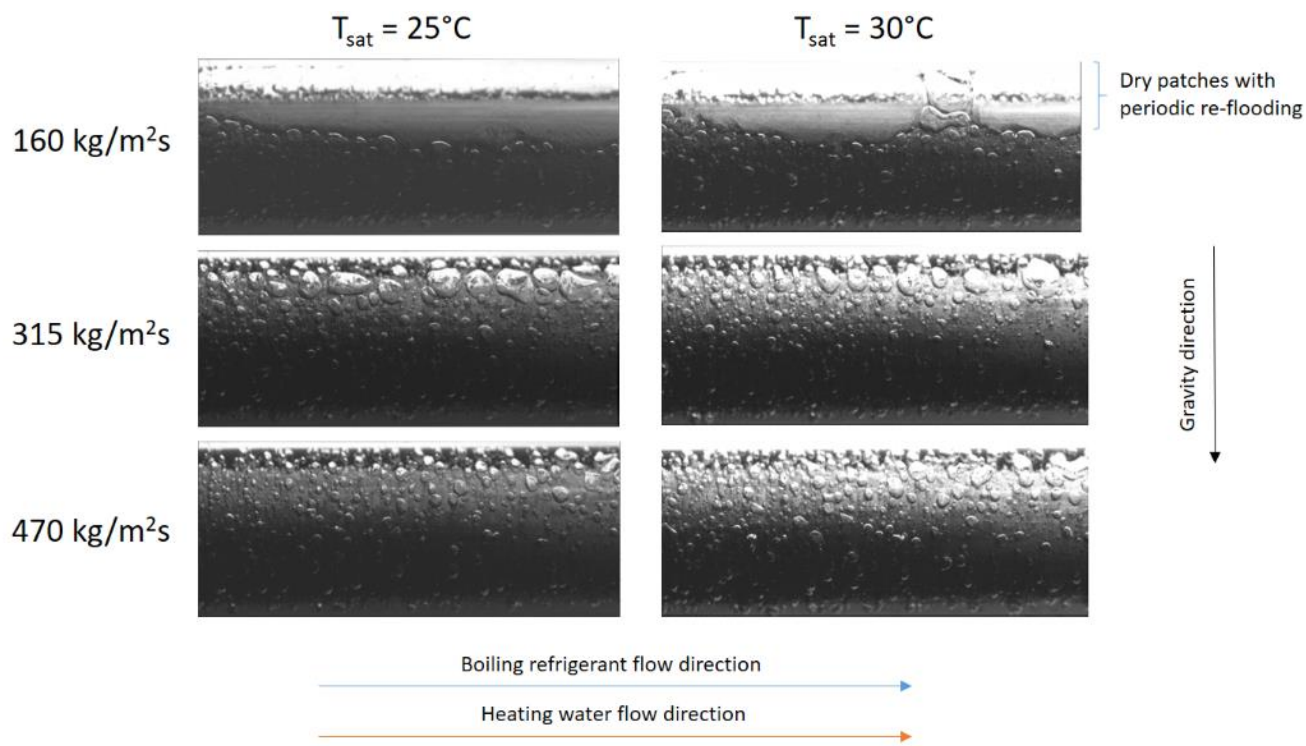


Fig. 3: Recordings of flow boiling of R245fa in co-current flow regime.
Periodic forming of dry patch and reflooding was present on the surface at the lowest mass velocity of 160 kg/m$^2$s.

To determine the heat flux density in co-current flow configuration, the first two water thermocouples on the test section were used. As surface temperature decreases along the flow due to the heat transfer from water to refrigerant, the temperature difference between the first two thermocouples corresponds to the highest measurable heat flux value along the section. Results for the saturation temperature $T_{sat}$ = 25°C as a function of refrigerant mass velocity are shown on Figure 4. As expected, higher mass velocities always correspond to higher surface heat flux densities. The increase of heat flux density with the mass velocity is large at the beginning, while it is slower at higher values. This can be explained with bubble dynamics shown in Figure 3. At the lowest mass velocity, the occurrence of periodical vapour patches (plugs) reduces the overall heat flux density to the account of solid-vapour heat transfer, which is significantly lower than in the case of steady flow boiling regime. In the dry patch region, no evaporation is present and therefore no latent heat is removed. A high initial increase of heat flux density follows, when large vapour patches can no longer be formed and surface remains wetted for longer time periods. Further increase of mass velocity contributes to lower increase of heat flux density, as bubble dynamics remain relatively unchanged.  For determination of the exact mass velocity, where the formation of larger vapour patch is no longer possible more measurements would be required.

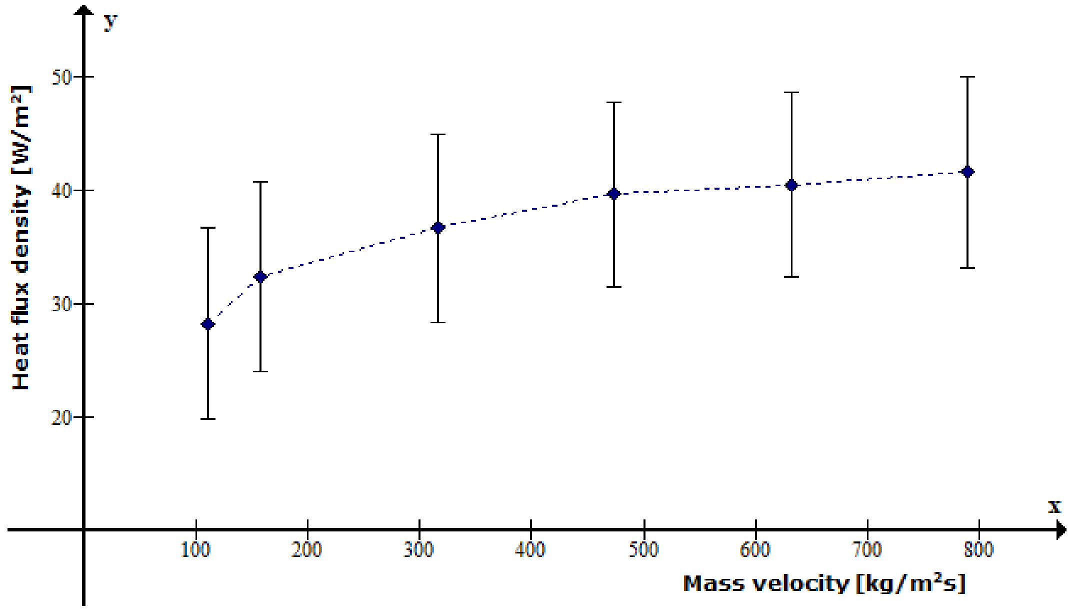


Fig. 4: Heat flux density as a function of refrigerant mass velocity.
Measured at $T_{sat}$ = 25°C, subcooling 3°C and heating water at 60°C.

The uncertainty of heat flux density measurements was determined with a Monte Carlo method. Random noise within known uncertainty of ± 0.5°C was added to the measured temperatures and variation of calculated heat flux density was observed. The obtained uncertainty is approximately ± 8.5 W/$m^2$ and ranges from 20% to 27%, depending primarily on the refrigerant flow rate. We expect to reduce this value by using more thermocouples and proper calibration before each test.

## 4. Conclusion

Flow boiling of refrigerant R245fa was investigated on a horizontal temperature-controlled annular test section. The flow boiling patterns were observed at different mass flow rates, two different saturation temperatures and two different flow regime configurations. Visualization of the two-phase flow patterns in the counter-current flow operation enabled the observation of different boiling flow regimes, from stable dry patch formation, through high-vapour quality plug flow to steady flow boiling at low vapour quality. The observation of flow patters in co-current operation enabled the highest possible surface superheats. Heat flux density in this regime was determined for different flow rates and explained with basic bubble phenomena. The results show, that the effect of flow rate on heat transfer is most noticeable at the transition from plug flow to steady flow boiling, as heat transfer in occasional vapor-solid interaction during periodic dryouts is significantly lower.

Future work includes performing measurements at different test section inclinations (most notably vertical), and quantification of crucial boiling parameters from the recordings, such as bubble release frequency, nucleation site density and bubble size distribution.

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